PAIR PRODUCTION ABSORPTION TROUGHS IN GAMMA-RAY BURST SPECTRA: A POTENTIAL DISTANCE DISCRIMINATOR

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ABSTRACT

In order to explain the emergence of a high-energy continuum in gamma-ray bursts (GRBs) detected by EGRET, relativistic bulk motion with large Lorentz factors has recently been inferred for these sources regardless of whether they are of galactic or cosmological origin. This conclusion results from calculations of internal pair production opacities in bursts that usually assume an infinite power-law source spectrum for simplicity, an approximation that is quite adequate for some bursts detected by EGRET. However, for a given bulk Lorentz factor Γ, photons above the EGRET range can potentially interact with sub-MeV photons in such opacity calculations. Hence it is essential to accurately address the spectral curvature in bursts seen by BATSE, and also treat the X-ray paucity that is inferred from low energy fluxes observed in the X-ray band. In this paper we present the major properties induced in photon-photon opacity considerations by such spectral curvature. The observed spectral breaks around 1 MeV turn out to be irrelevant to opacity in cosmological bursts, but are crucial to estimates of source transparency in the 1 GeV – 1 TeV range for sources located in the galactic halo. We find that broad absorption troughs can arise at these energies for suitable bulk motion parameters Γ. Such troughs are probably an unambiguous signature of a galactic halo population, and if observed by experiments such as Whipple, MILAGRO and GLAST, would provide powerful evidence that such bursts are not at cosmological distances.

Subject headings: gamma-rays: bursts — radiation mechanisms: non-thermal — gamma rays: theory — relativity

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1. INTRODUCTION

High energy gamma-rays have been observed for six gamma-ray burst sources by the EGRET experiment on board the Compton Gamma-Ray Observatory (CGRO). Most conspicuous among these observations is the emission of an 18 GeV photon by the GRB940217 burst (Hurley et al. 1994). These detections occurred during the first five years of the mission, when the EGRET spark chamber gas level was not severely depleted and, taking into account the instrumental field of view, they indicate that emission in the 1 MeV–10 GeV range is probably common among bursts, if not universal. One implication of GRB observability at energies around or above 1 MeV is that, at these energies, two-photon pair production ($\gamma\gamma \to e^+e^-$) is not producing any significant spectral attenuation in the source. Attenuation by pair creation in the context of GRBs was first explored by Schmidt (1978). He assumed that a typical burst produced quasi-isotropic radiation, and concluded at the time that the detection of photons around 1 MeV limited bursts to distances less than a few kpc, since the optical depth scales as the square of the distance to the burst.

The observation by EGRET of emission above 100 MeV clearly indicated that Schmidt's analysis needed serious revision. Furthermore, BATSE's determination of the spatial isotropy and inhomogeneity of bursts (e.g. Meegan et al. 1991, 1996) suggested that they are either in an extended halo or at cosmological distances. Consequently their intrinsic luminosities, and therefore their optical depths to pair production for isotropic radiation fields, are much higher than previously believed. Hence the suggestion that GRB photon angular distributions were highly beamed and produced by a relativistically moving or expanding plasma (e.g. Fenimore et al. 1992) has become very popular. Various determinations of the bulk Lorentz factor Γ of the medium supporting the GRB radiation field have been made in recent years, mostly concentrating (e.g. Krolik and Pier 1991, Baring 1993, Baring and Harding 1993, Harding 1994) on the simplest case where the angular extent of the source was of the order of $1/\Gamma$. These calculations assumed an infinite power-law burst spectrum, and deduced that gamma-ray transparency up to the maximum energy detected by EGRET required $\Gamma \gtrsim 5$ for galactic halo sources and $\Gamma \gtrsim 200$ for cosmological bursts. These limits are reproduced by a wide range of source geometries (Baring and Harding 1996).

While the assumption of an infinite power-law source spectrum is expedient, the spectral curvature seen in most GRBs by BATSE (e.g. Band et al. 1993) is expected to play an important role in reducing estimates for Γ for potential TeV emission from these sources. Such curvature is patently evident in 200 keV–2 MeV spectra of EGRET-detected bursts, and its prevalence in bursts is indicated by the generally steep EGRET spectra for bursts (e.g. Schneid et al. 1992; Kwok et al. 1993; Sommer et al. 1994; Hurley et al. 1994). Furthermore, the relative paucity of emission detected below 10 keV in a number of GRBs (e.g. Epstein 1986) can potentially lower the opacity for the highest energy photons substantially. In this paper, the principal effects introduced into pair production opacity calculations by spectral curvature over the BATSE energy range and the lower portions of the EGRET domain are considered. We find that the presence of such curvature generally has minimal influence on the spectra and inferred bulk motions for bursts of cosmological origin. In contrast, for galactic halo sources, we observe that for realistic parameters

of the bulk motion, source opacity may arise only in a portion of the 1 GeV – 1 TeV range, with transparency returning in the super-TeV range, resulting in the appearance of distinctive broad absorption troughs. Such features may provide a unique identifier for bursts in halo locales, so that current and future ground-based initiatives such as Whipple and MILAGRO, and space missions such as GLAST may play a key role in determining the distance scale for gamma-ray bursts.

2. γ-γ ATTENUATION AND SPECTRAL CURVATURE

In assessing the role of two-photon pair production in burst spectral attenuation, the interactions of photons created only within the emission region are considered here. Recent authors have invoked relativistic beaming in sources when superseding Schmidt's (1978) early work. This hypothesis builds on the property that $\gamma\gamma \to e^- e^+$ has a threshold energy E_1 that is strongly dependent on the angle Θ between the photon directions: $E_1 > 2m_e^2c^4/[1-\cos\Theta]E_2$ for target photons of energy E_2. Hence radiation beaming associated with relativistic bulk motion of the underlying medium can dramatically reduce the optical depth $\tau_{\gamma\gamma}$ in sources at enormous distances from earth, suppressing γ-ray spectral attenuation turnovers and blueshifting them out of the observed spectral range. The simplest picture of relativistic beaming has "blobs" of material moving with a bulk Lorentz factor Γ more-or-less toward the observer, and having an angular "extent" $\sim 1/\Gamma$ (Krolik and Pier 1991, Baring 1993, Baring and Harding 1993). These works assumed an infinite power-law spectrum $n(\varepsilon) = n_\gamma\,\varepsilon^{-\alpha}$, where ε is the photon energy in units of m_ec^2, for which the optical depth to pair creation assumes the form $\tau_{\gamma\gamma}(\varepsilon) \propto \varepsilon^{\alpha-1}\Gamma^{-(1+2\alpha)}$ for $\Gamma \gg 1$.

Approximating the source photon spectrum by an infinite power-law is expedient, however most bursts detected by BATSE show significant spectral curvature in the 30 keV–500 keV range (e.g. Band et al. 1993). Furthermore, BATSE sees MeV-type (i.e. 500 keV–2 MeV) spectral curvature with significant frequency in bright bursts: see Schaefer et al. (1992) for an analysis of a brightness-selected sample from early in the BATSE era. EGRET observes three of the Schaefer et al. sources with such "high energy" breaks (Schneid et al. 1992; Kwok et al. 1992), and later EGRET bursts also exhibit "MeV-type breaks" — for relevant parameters, see Table 1. Hence, EGRET detections seem correlated with spectral breaks at the upper end of the BATSE energy range, which is probably a selection effect for the observability of bursts by EGRET: GRBs with breaks at higher energies tend to be more luminous in the super-MeV range. Whether bursts with breaks at MeV energies are a class of objects distinct from the majority that turnover at lower energies remains to be seen. The MeV-type breaks and those generally seen at lower energies in the BATSE data for many GRB spectra could, in principle, reduce the opacity of potential TeV emission from these sources, so it is important to generalize the pair production opacity/relativistic beaming analysis to include the effects of spectral curvature.

The effects of a depletion of low energy photons in the BATSE range relative to the EGRET quasi-power-law spectra can quickly be determined by taking the simplest approximation to spectral curvature, namely a power-law broken at a dimensionless energy $\varepsilon_{\rm B}$ $(= E_{\rm B}/0.511\,{\rm MeV})$ with a low

energy cut-off at $\varepsilon_{\rm C}$:

$$n(\varepsilon) \;=\; n_\gamma \varepsilon_{\rm B}^{-\alpha_h} \begin{cases} 0, & \text{if } \varepsilon \leq \varepsilon_{\rm C} \;\;, \\ \varepsilon_{\rm B}^{\alpha_l} \varepsilon^{-\alpha_l}, & \text{if } \varepsilon_{\rm C} \leq \varepsilon \leq \varepsilon_{\rm B} \;\;, \\ \varepsilon_{\rm B}^{\alpha_h} \varepsilon^{-\alpha_h}, & \varepsilon > \varepsilon_{\rm B} \;\;. \end{cases} \tag{1}$$

The optical depth determination for such a distribution follows the above description for pure power-laws, and utilizes results obtained in Gould and Schreder (1967) and Baring (1994) for truncated power-laws. The details of our calculations are presented in Baring and Harding (1997, in preparation, hereafter BH97), where the optical depth $\tau_{\gamma\gamma}(\varepsilon)$ for pair production attenuation of a broken power-law photon distribution is found to be

$$\frac{\tau_{\gamma\gamma}(\varepsilon)}{n_\gamma \sigma_{\rm T} R} \;\approx\; \frac{\mathcal{A}(\alpha_l)}{\varepsilon_{\rm B}^{\alpha_h-\alpha_l}} \Bigl\{ \mathcal{H}(\alpha_l,\, \eta_{\rm C}) - \mathcal{H}(\alpha_l,\, \eta_{\rm B}) \Bigr\} \frac{\varepsilon^{\alpha_l-1}}{\Gamma^{2\alpha_l}} + \mathcal{A}(\alpha_h)\, \mathcal{H}(\alpha_h,\, \eta_{\rm B})\, \frac{\varepsilon^{\alpha_h-1}}{\Gamma^{2\alpha_h}} \quad , \tag{2}$$

where $\eta_{\rm B} = \max\{1,\ \sqrt{\varepsilon_{\rm B}\varepsilon}\,/\Gamma\,\}$ and $\eta_{\rm C} = \max\{1,\ \sqrt{\varepsilon_{\rm C}\varepsilon}\,/\Gamma\,\}$, and

$$\mathcal{H}(\alpha,\, \eta) \;=\; \frac{4}{\sigma_{\rm T}} \int_1^\infty d\chi\, \frac{q^{2(1+\alpha)}}{\chi^{2\alpha-1}}\, \sigma_{\gamma\gamma}(\chi) \;, \quad q = \min\Bigl(1,\ \frac{\chi}{\eta}\Bigr) \;, \tag{3}$$

for $\sigma_{\gamma\gamma}$ being the pair production cross-section. Here $\chi = [\varepsilon\omega(1-\cos\Theta)/2]^{1/2}$ is the center-of-momentum frame (CM) energy of the photons, for Θ being the angle between the directions of photons of dimensionless energies ε (test photon) and ω (interacting). The pair production threshold condition is then $\chi \geq 1$. The function $\mathcal{H}(\alpha,\, \eta)$ is equivalent, up to a factor of 4, to that in Eq. (23) of Gould and Schreder (1967). The specialization $\mathcal{H}(\alpha,\, 1)$ can be approximated by $7/(6\alpha^{5/3})$ (e.g. Baring 1994) to better than 1% for $1 < \alpha < 7$. Setting $\alpha_l = \alpha_h$ also reproduces the infinite power-law dependence $\tau_{\gamma\gamma}(\varepsilon) \propto \varepsilon^{\alpha_h-1}\Gamma^{-1-2\alpha_h}$, remembering that $n_\gamma \propto fd^2/R^2$ for fluxes measured at earth of $f = 4\pi n_\gamma c R^2/d^2$ at 511 keV per 511 keV and source size $R = R_v\Gamma$ and source distance d. We choose a variability "size" $R_v = 3\times 10^7$ cm here, following Baring and Harding (1996). Note that $\mathcal{A}(\alpha)$ is a function that arises from the integrations over photon angles, and is approximately given (to 1%, Baring 1994) by $2/(4/3{+}\alpha)^{27/11}$. More gradual spectral curvature can be treated by fitting the GRB continuum with piecewise continuous power-laws, generalizing the structure inherent in Eq. (2); our technique is well-suited to this adaptation (discussed in BH97).

A remarkable feature of Eq. (2) is that the optical depth is no longer necessarily a monotonically increasing function of energy ε. The parameters $\eta_{\rm B}$ and $\eta_{\rm C}$ govern the importance, or otherwise, of spectral curvature effects. Clearly, if either $\varepsilon_{\rm B}$ or ε (in m_ec^2) is low enough or Γ large enough that $\eta_{\rm B} = 1$, then the pure power-law result emerges from Eq. (2) and curvature effects are negligible. Such a situation might then be expected for cosmological bursts. Conversely if $\eta_{\rm B}$ or $\eta_{\rm C}$ exceed unity, the shape of the BATSE spectrum becomes crucial to optical depth estimates. The spectra in Eq. (1) were attenuated using the optical depth in Eq. (2), specifically via an exponential factor $\exp\{-\tau_{\gamma\gamma}\}$, for fluxes and spectra typical of bright gamma-ray bursts (e.g. see Table 1); the emergent spectra are depicted in Fig. 1. The results for the cosmological case are noticeably uninteresting: the input broken power-law is modified (as expected intuitively) by a quasi-exponential turnover at an energy that is an increasing function of the bulk Lorentz

factor Γ of the expansion that generates the radiation. If Γ were chosen large enough to permit emission out to TeV energies, the spectra would suffer attenuation due to the *external* supply of cosmological infra-red background photons (Stecker and De Jager 1996, Mannheim et al. 1996). Note that opacity skin effects can sometimes render the exponential $\exp\{-\tau_{\gamma\gamma}\}$ a poor descriptor of attenuation, with $1/(1+\tau_{\gamma\gamma})$ perhaps being an improvement, leading to broken power-laws rather than exponential turnovers. Such alternatives, which are model-dependent, do not qualitatively affect the conclusions drawn here and are discussed in BH97.

The galactic halo case in Fig. 1, where typically $\eta_{\rm B} \gtrsim 1$, exhibits remarkably different behaviour: broad absorption features occur in the 1 GeV–1 TeV range, depending on the choice of source Γ. The presence of these notable troughs, which become more pronounced as Γ decreases, results from the non-monotonic behaviour of the optical depth with energy: $\tau_{\gamma\gamma}$ drops below unity around the TeV range due to the "depleted supply" of interacting photons in the low energy BATSE portion of the spectrum. These distinctive features arise only for large spectral breaks (i.e. $\delta\alpha = |\alpha_h - \alpha_l| \gtrsim 1.3$), and also MeV-type break energies; a reduction of the severity or energy of the break pushes the attenuation towards the more familiar exponential turnovers depicted in Fig. 1. The appearance of the troughs is most strongly dependent on the size of $\delta\alpha$ and on α_l being not too large. Consequently, from the data in Table 1, it appears that GRBs 910601 and 910814 would be the strongest candidates for producing features like those exhibited in Fig. 1. The other EGRET bursts are in a marginal regime of parameter space; attenuation results for them are discussed in BH97. Note that the structure on the low energy end of the troughs is a product of the sharp spectral breaks used, and is smoothed out (BH97) for more realistic spectral curvature.

Attenuation of spectra appropriate to the burst GRB 910814 are depicted in Fig. 2 for different Γ. The case where there is no low energy cutoff yields an extremely broad trough, that is more reminiscent of a "shelf." Such behaviour differs from the halo cases in Fig. 1 because here the source spectra are somewhat steeper, producing much broader troughs; the result would be an improbability of observing sources like GRB 910814 at TeV energies when no low energy cutoff is present. In contrast, when a spectral cutoff is present at 5 keV in Fig. 2 (which is below the threshold of BATSE sensitivity), mimicking the X-ray paucity of bursts (Epstein 1986; actually this is a paucity of energy in X-rays, so that it may be better described by a significant spectral break), the supply of interacting photons is further depleted, the troughs narrow and TeV emission reappears. This property clearly underlines the importance of the relationship between the 10 GeV–1 TeV and the soft X-ray portions of the GRB spectrum, correlations that can only be analyzed using broad band observations of bursts. Note that the highest EGRET spectral point for GRB 910814 in Fig. 2 indicates that the bulk Lorentz factor is constrained to $\Gamma \gtrsim 20$.

The array of spectral shapes depicted in Figs. 1 and 2 indicates that a diversity of such forms must be anticipated in GRBs, with troughs, shelfs and turnovers, depending on source spectral parameters (see BH97). The reason for the appearance of troughs in the galactic halo case but not for cosmological distances stems from the much higher photon densities inferred in cosmological sources for a given flux at earth, for which photon-photon collisions primarily involve photons well

above 1 MeV, and spectral curvature in the BATSE range is irrelevant. Note that the model-dependent details of pair cascading have been neglected here; these are discussed in BH97.

3. IMPLICATIONS

The importance of the spectral attenuation results presented here is immediately apparent. The absorption troughs in Figs. 1 and 2 cannot be produced for large source distances and are unambiguous markers of a galactic halo burst population; they are consequently a potentially powerful observational diagnostic. Observations by the air Čerenkov detectors Whipple and MILAGRO (a new water tank experiment) at the 300 GeV–5 TeV range, and perhaps even HEGRA at higher energies, combined with a probing of the 100 MeV – 100 GeV range by future space instrumentation such as GLAST (a spark chamber experiment) could confirm or deny the existence of such absorption features. Note that the observation of apparently sharp cutoffs would not distinguish between cosmological or galactic burst hypotheses. The current Whipple sensitivity threshold (Connaughton et al. 1995) is not sufficiently constraining, so future generations of experimentation will be required to assess whether or not GeV–TeV troughs are present in GRB spectra. Having five times the field of view and around ten times the sensitivity of EGRET, and therefore the potential to detect dozens of bright bursts per year, the proposed GLAST mission (Michelson 1996) might be expected to make significant inroads into this problem.

The shape and position of these prominent features are strongly dependent on the spectral slopes and fluxes in the BATSE and EGRET ranges, and even more interestingly, on the contributions to the source flux from below 10 keV. Hence coupled X-ray, soft and hard gamma-ray observations are clearly warranted, an exciting challenge to the astronomy and GRB communities. The strong and well-defined correlations between the width and shape of the troughs and the spectral curvature below 10 MeV act as clear markers of the pair production attenuation analysis discussed here, and are unlikely to be replicated in detail by alternative, multi-component models (e.g. Katz 1994, Mészáros and Rees 1994) of hard gamma-ray emission, or from opacity due to external background fields of radiation (such attenuation is generally above 100 GeV: Stecker and De Jager 1996, Mannheim, et al. 1996). In summary, this paper presents a patently powerful spectral diagnostic in the super-GeV range that can provide enticing prospects for solving the problem of gamma-ray burst location.

We thank Dieter Hartmann, Bob Gould, Jay Norris and David Thompson for reading the manuscript, and Brenda Dingus and Jennifer Catelli for discussions about EGRET burst data.

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TABLE 1
PARAMETERS FOR BURSTS WITH SPECTRAL BREAKS

GRB	E_B (MeV)	BATSE α_l	BATSE α_h	EGRET α_h
910503	0.4 ± 0.2	0.7 ± 0.1	2.1	2.2 ± 0.2
910601	0.6 ± 0.2	1.0 ± 0.1	steep	3.7 ± 0.2
910814	1.2 ± 0.1	0.9 ± 0.1	steep	2.8 ± 0.2
930131	0.7 ± 0.1	1.2 ± 0.1	2.5	2.0 ± 0.2
940217	0.8 ± 0.1	1.2 ± 0.2	...	2.5 ± 0.2

NOTE.— The values of the break energy E_B and the spectral index below (α_l) and above (α_h) the break for five of the six bursts observed by both BATSE and EGRET. For the first three bursts, the BATSE parameters are taken from Band et al. (1993, the Band model fit; the "steep" entries indicate the inability of the fit to pin down the hard tail), while the remaining BATSE data were obtained for GRB 930131 from Kouveliotou et al. (1994) and for GRB 940217 from Hurley et al. (1994, who quote no BATSE result for α_l). The high-energy spectral indices (α_h) as determined by EGRET are from Schneid et al. (1992: GRB 910503) and Kwok et al. (1993: GRBs 910601 and 910814), Sommer et al. (1994: GRB 930131) and Hurley et al. (1994: GRB 940217).

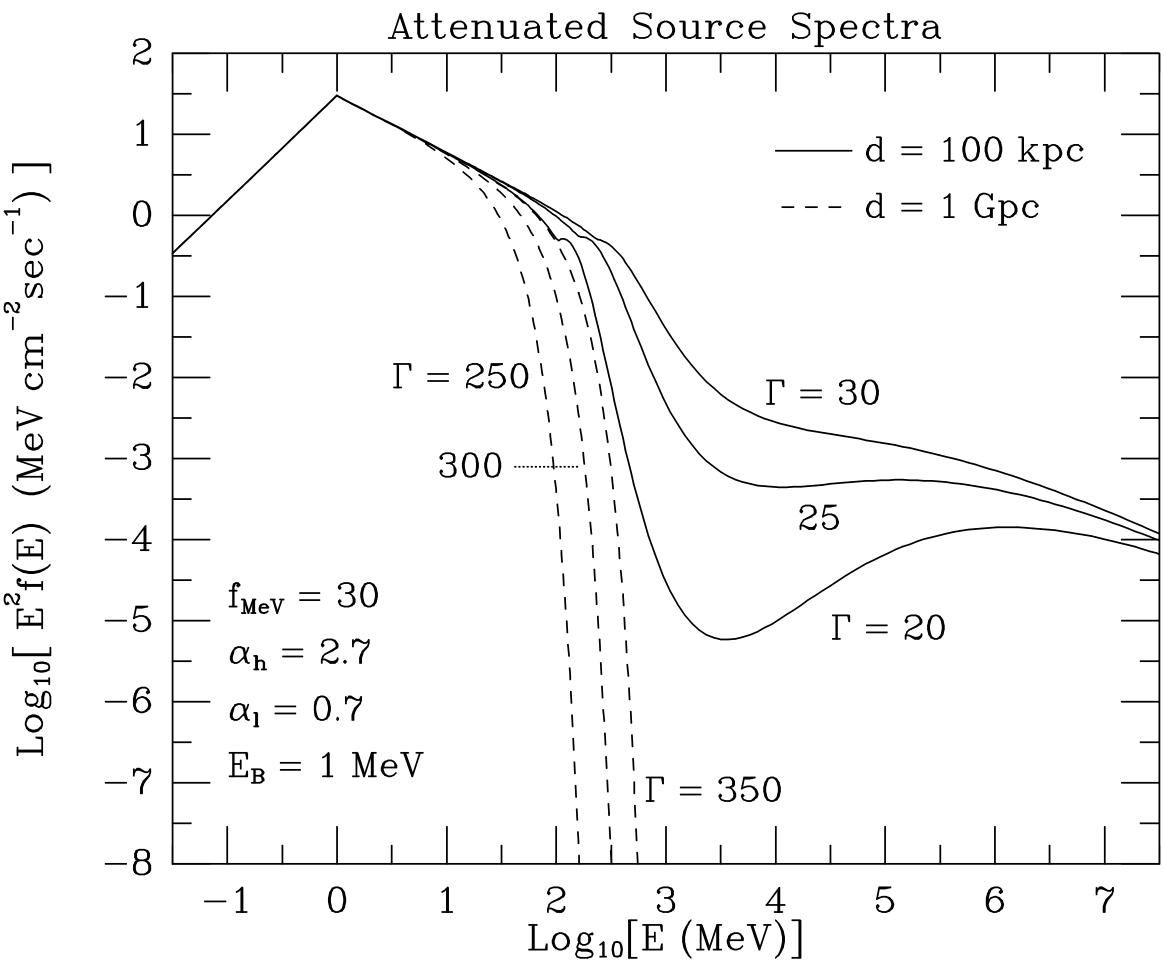

Fig. 1.— The attenuation, internal to the source, of a broken power-law spectrum [see Eq. (1) for definition], for source distances typical of galactic halo (solid curves) and cosmological (dashed curves) populations, and different bulk Lorentz factors Γ for the emitting region, as labelled. The spectra, plotted in the $E^2\, f(E)$ (i.e. νF_ν) format, are attenuated by pair creation according to the factor $\exp\{-\tau_{\gamma\gamma}\}$ for optical depths determined via Eq. (2) (i.e. no pair cascading is included). Here no low energy cutoff was used, i.e. $\varepsilon_{\rm C} = 0$. The quasi-exponential turnovers of the cosmological cases can provide lower bounds to Γ using current EGRET data, and contrast the broad absorption troughs of the halo examples.

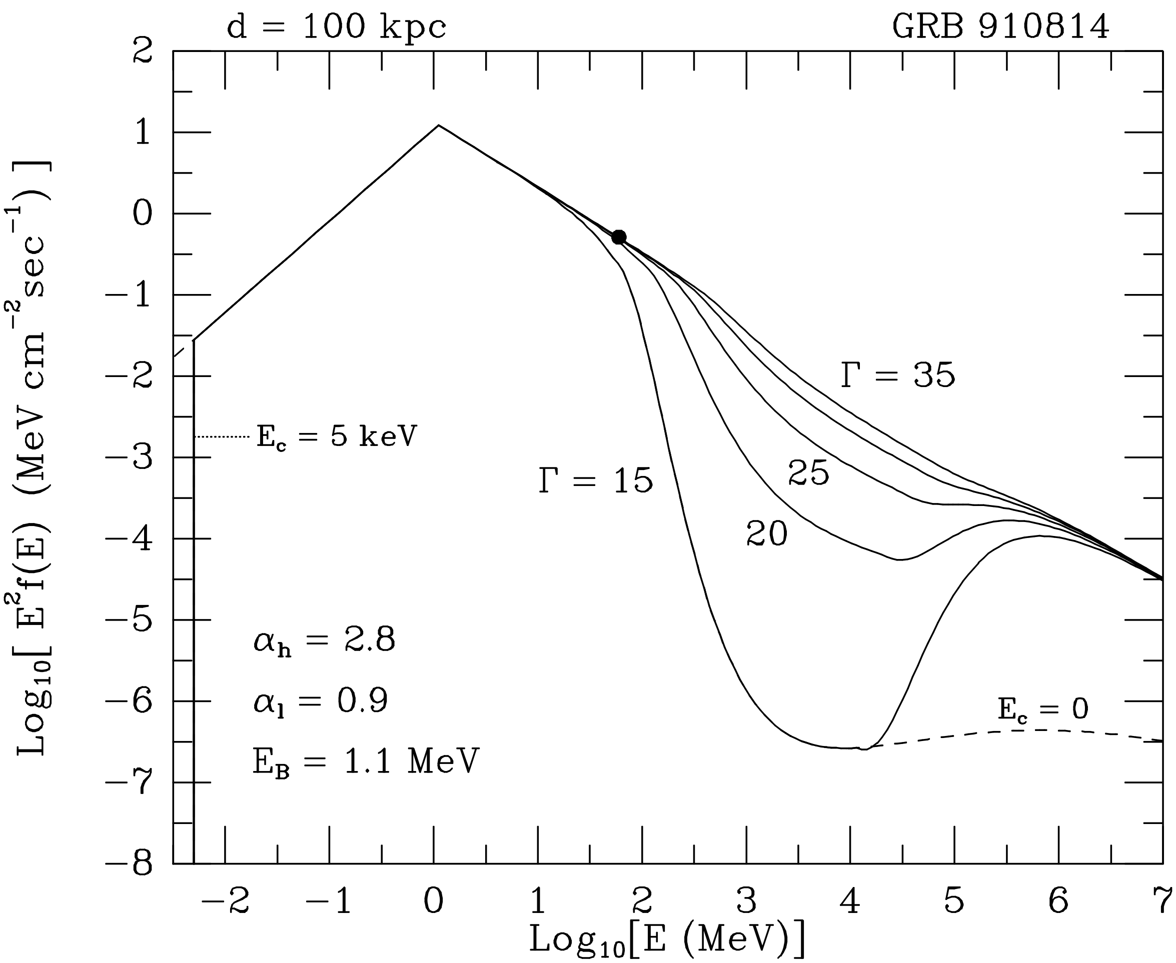

Fig. 2.— Pair production (internal) attenuation of a broken power-law fit (again in $E^2 f(E)$ format) to the GRB 910814 spectrum, for a galactic halo source distance of 100 kpc, for radiation emanating from regions of different bulk Lorentz factors Γ, incremented by 5, as labelled. The power-law parameters for Eq. (1) were obtained from Table 1 and the solid curves correspond to a low energy cutoff at $E_{\rm C} = 5\,{\rm keV}$. The dashed curve displays the $\Gamma = 15$ case for no cutoff (i.e. $E_{\rm C} = 0$). The dot marks the highest EGRET data point, at 60 MeV.